2nd year PhD seminar - CAT

Antiprotons deceleration and transport for antihydrogen production in the GBAR experiment at CERN

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01/06/2020

Equivalence principle

The effect of gravitation on a body in free fall
is independent from its nature and composition

- One of the bases of General Relativity
- Verified with a precision of 10^{-15} for matter (MICROSCOPE satellite [1])
- Never tested with antimatter ($\bar{g}$)
- Beyond the standard model: antigravity, different constant …?

[1] H. Pihan-le Bars et al., "New Test of Lorentz Invariance Using the MICROSCOPE Space Mission" *Phys. Rev. Lett.* **123**, *231102,* (2019)

GBAR experiment

Gravitational Behaviour of Antihydrogen at Rest

- Other experiments: ALPHA-g, AEgIS
- GBAR ▶ Creation of an Antihydrogen ion $\overline{H}^+$

GBAR experiment

Gravitational Behaviour of Antihydrogen at Rest

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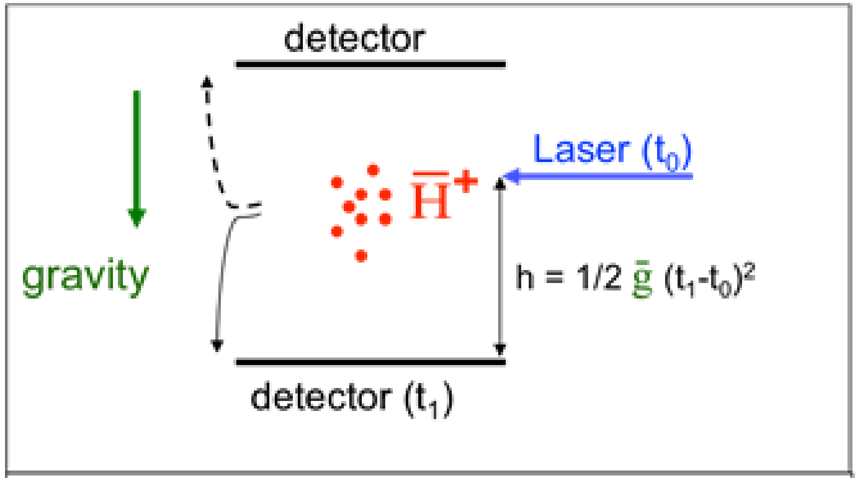
- GBAR ▶ Creation of an Antihydrogen ion $\overline{H}^+$

  ▶ Cooled down to µK temperatures

GBAR experiment

Gravitational Behaviour of Antihydrogen at Rest

- Other experiments: ALPHA-g, AEgIS
- GBAR
  - ▶ Creation of an Antihydrogen ion $\bar{H}^+$
  - ▶ Cooled down to µK temperatures
  - ▶ Photo-detachment
  - ▶ $\bar{H}$ free-fall



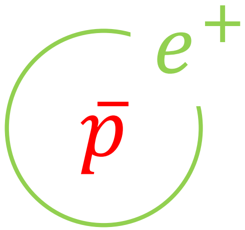
$\bar{H}^+$ production

$$(1) \quad \mathrm{Ps} + \bar{p} \longrightarrow \bar{H} + e^-$$

$\bar{H}^{+}$ production

$$(1)\qquad \mathrm{Ps} \quad + \quad \bar{p} \quad \longrightarrow \quad \bar{H} \quad + \quad e^{-}$$

$e^{-}e^{+}$



$\bar{H}^+$ production

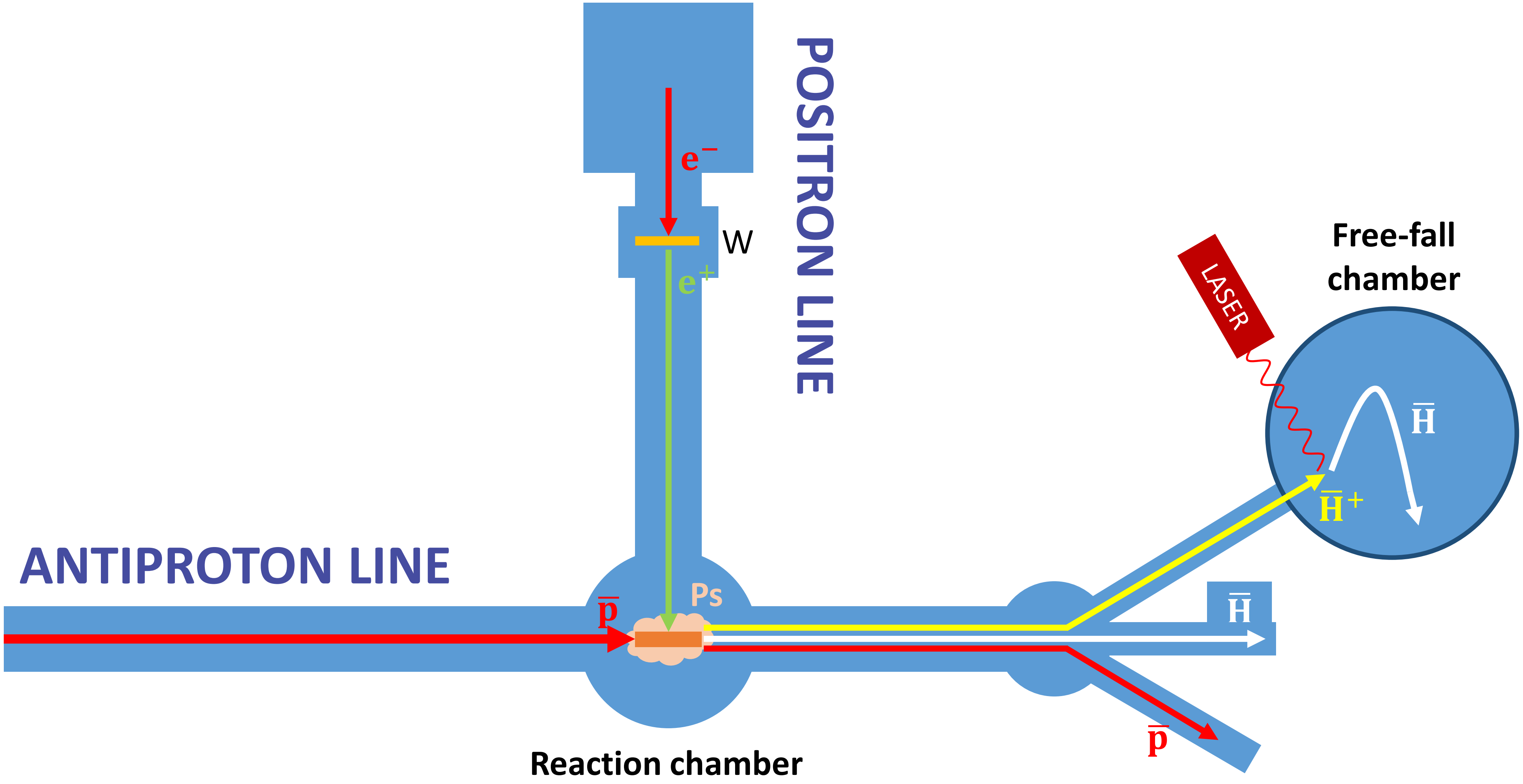
$$(1) \quad \mathrm{Ps} + \bar{p} \longrightarrow \bar{H} + e^-$$

$e^- e^+$ $\bar{p}\ e^+$

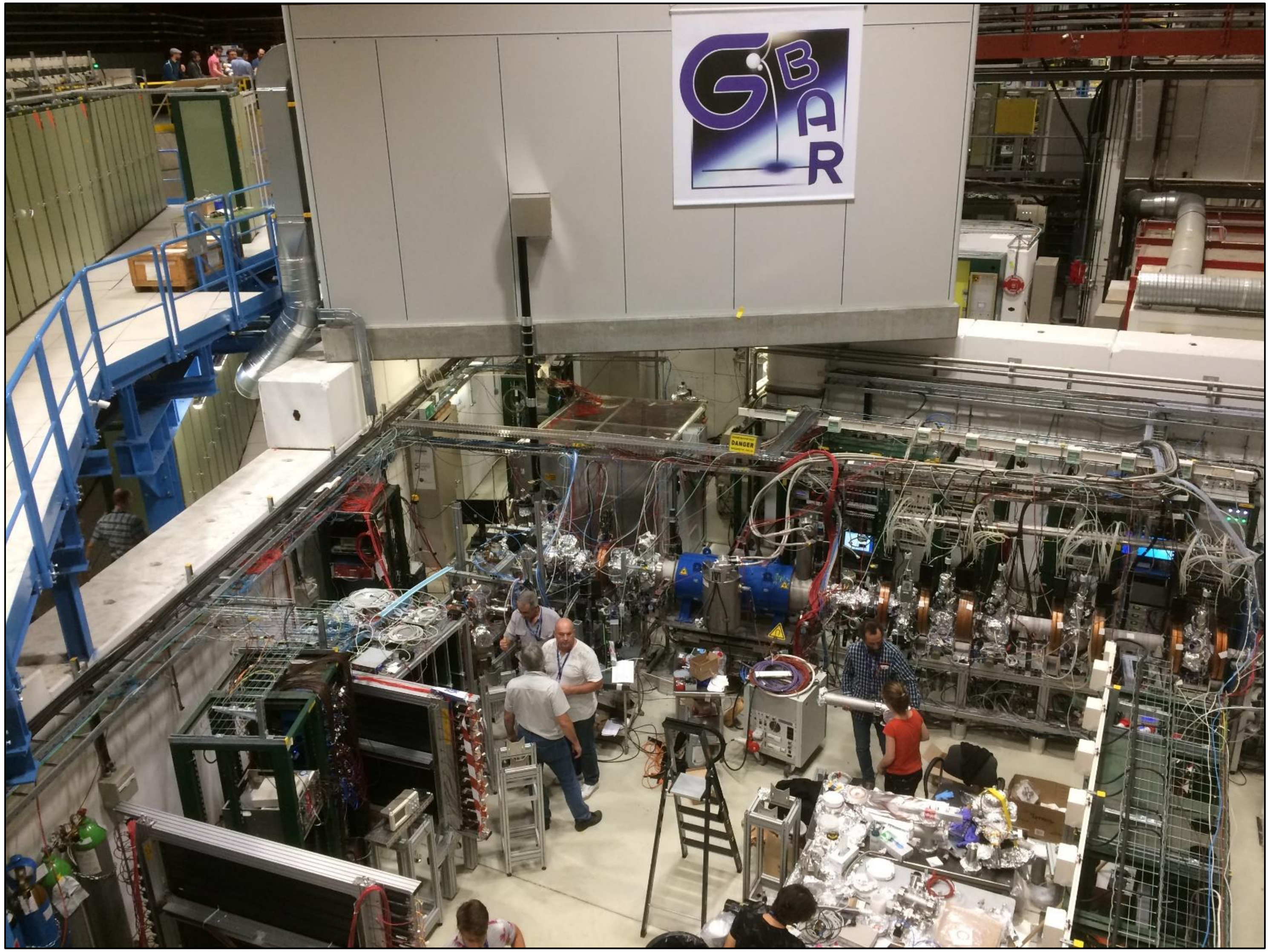
$$(2) \quad \bar{H} + \mathrm{Ps} \longrightarrow \bar{H}^+ + e^-$$

$\bar{p}\ e^+$ $e^- e^+$ $e^+\ \bar{p}\ e^+$

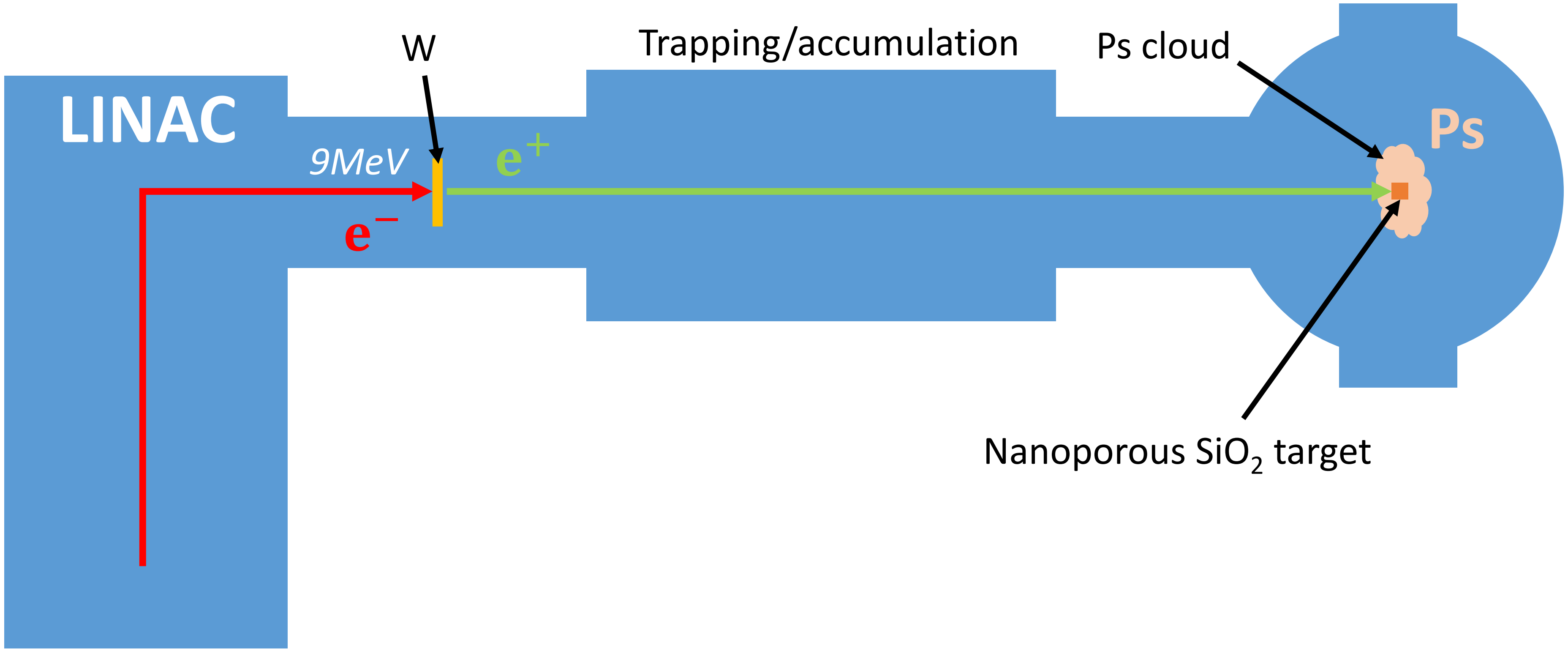
Experimental setup



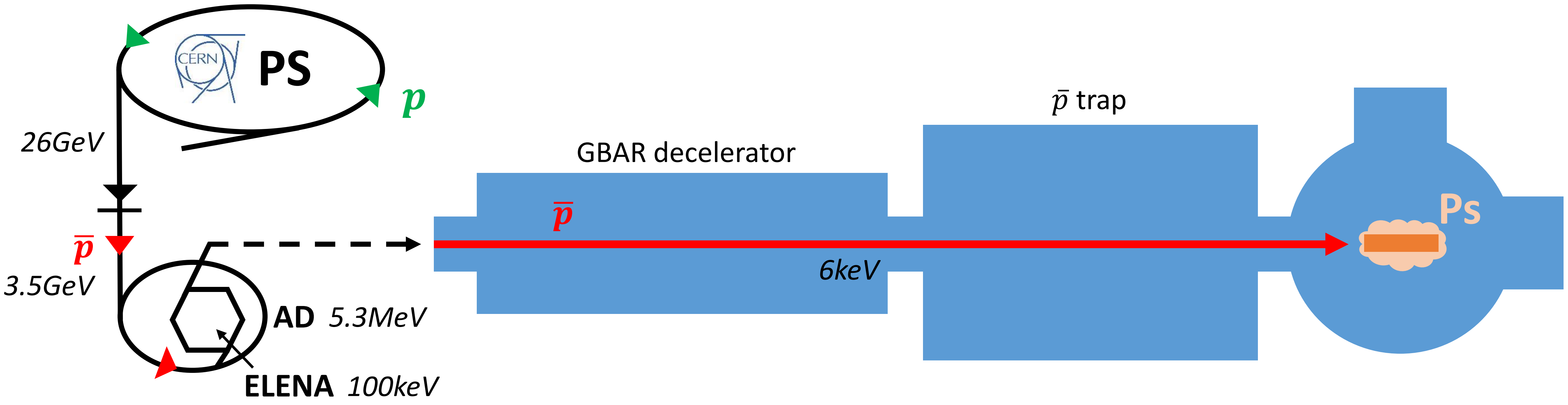
Experimental setup



Positron line

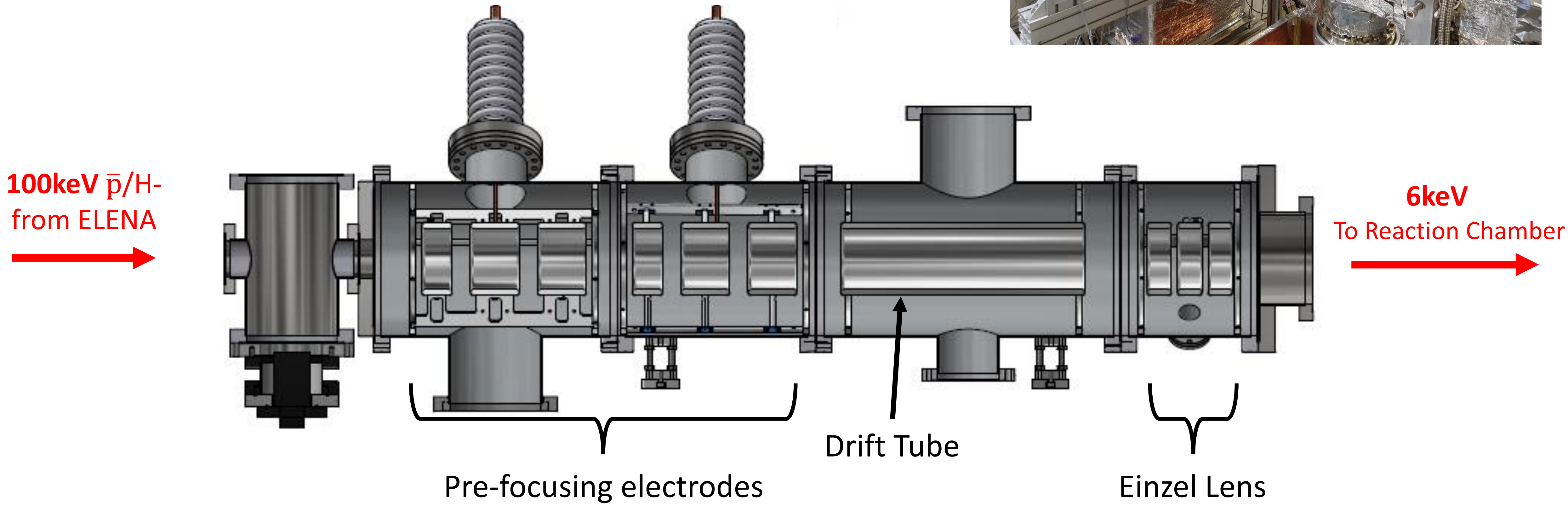


Antiproton line



Decelerator

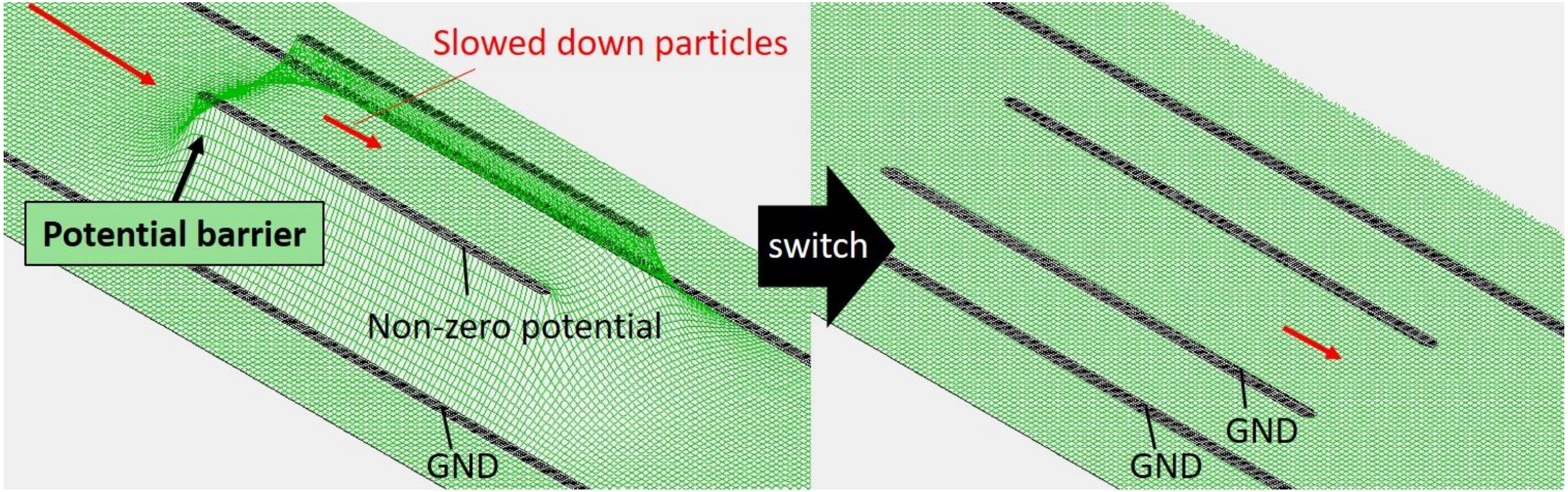
- Deceleration ensured by a **pulsed drift tube**



Decelerator

- Deceleration ensured by a **pulsed drift tube**: switch from high voltage to 0 while particles are inside

  <u>ex:</u> switch from 94kV to 0kV will decelerate the beam from 100keV to 6keV



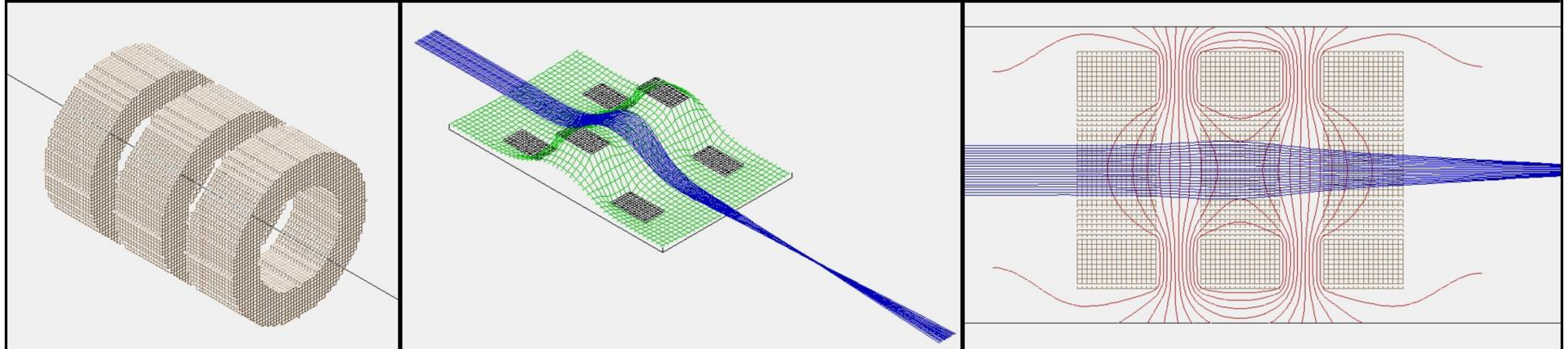
Negatively charged particles are repelled by the negative voltage

Particles are not re-accelerated when leaving the tube

Beam simulations

- Ion optics software: **SIMION**
- 3D meshing
- Laplace equation ▶ Potentials RK4 ▶ Trajectories

Simulation example: -> 8keV protons ->middle electrode potential = 6000V



3D view of geometry

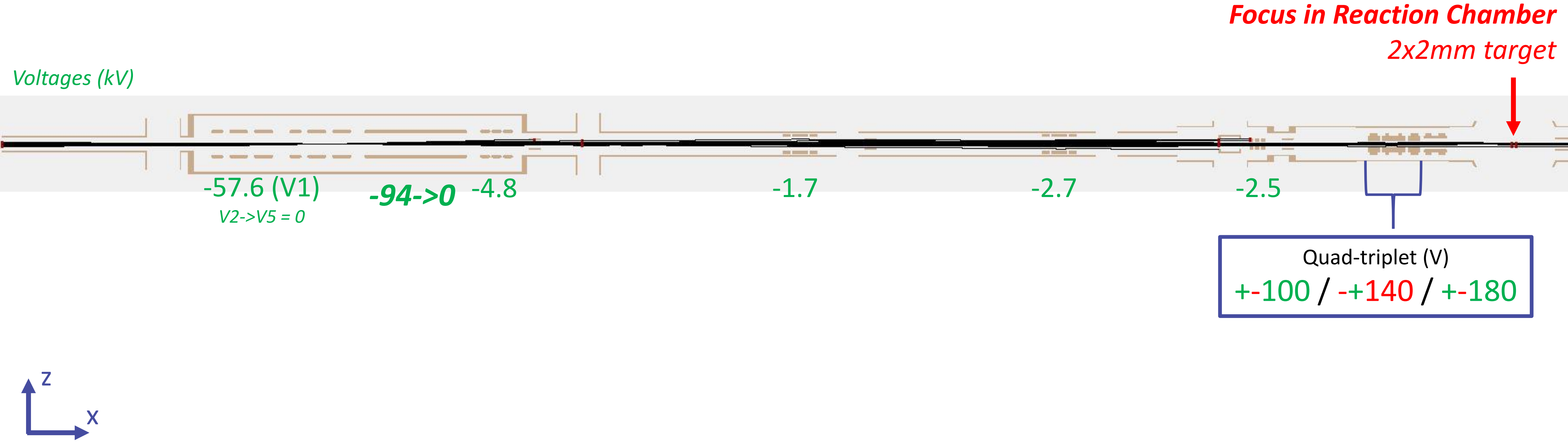
3D visualization of electric potentials (2D cross-sectional view)

equipotential lines (2D cross-sectional view)

Simulation of deceleration and transport

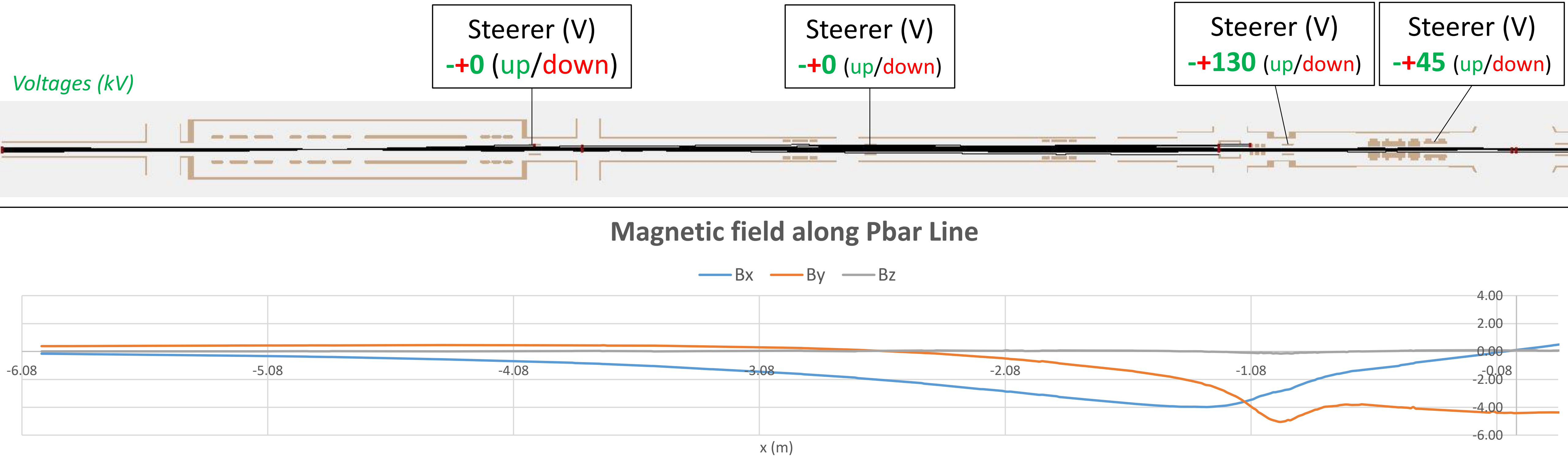
- Optimization of electrode voltages

▶ *Example for 2021 GBAR antiproton line:*



Simulation of deceleration and transport

- Optimization of electrode voltages
- Import magnetic field maps from Comsol and see the effect on pbar beam (stray field from positron line → beam pushed to the top)



Simulation of deceleration and transport

- Optimization of electrode voltages
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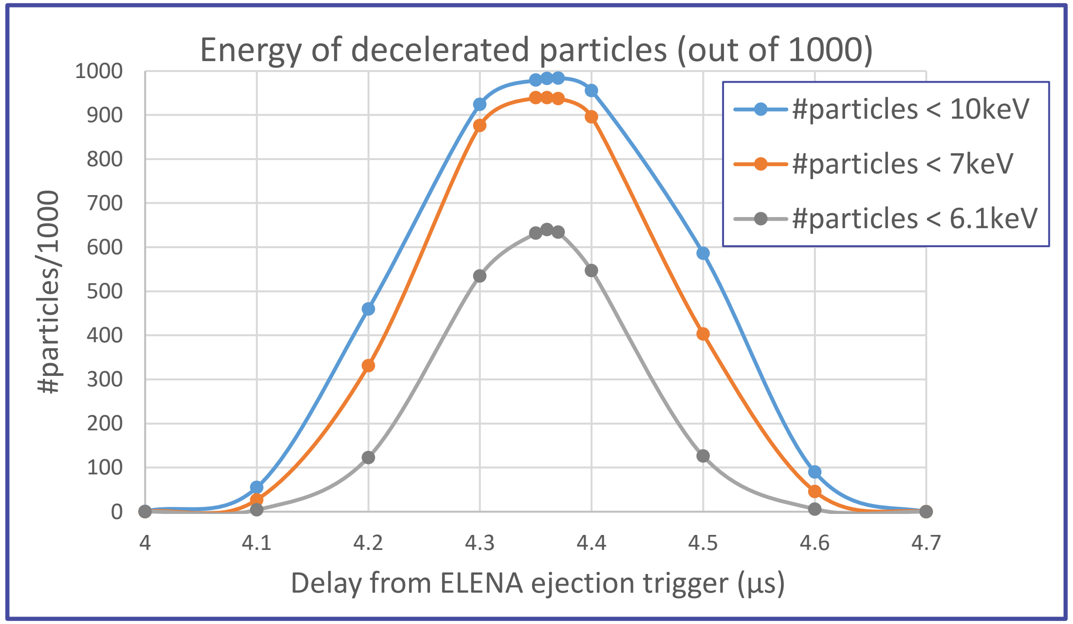
- Optimization of decelerator switch timing



Simulation of deceleration and transport

- Optimization of electrode voltages
- Import magnetic field maps from Comsol and see the effect on pbar beam (stray field from positron line)
- Optimization of decelerator switch timing
- Test optical lines designs before installing
- Provides a better comprehension of the beam and of all optical elements

Results of 2021 pbar run

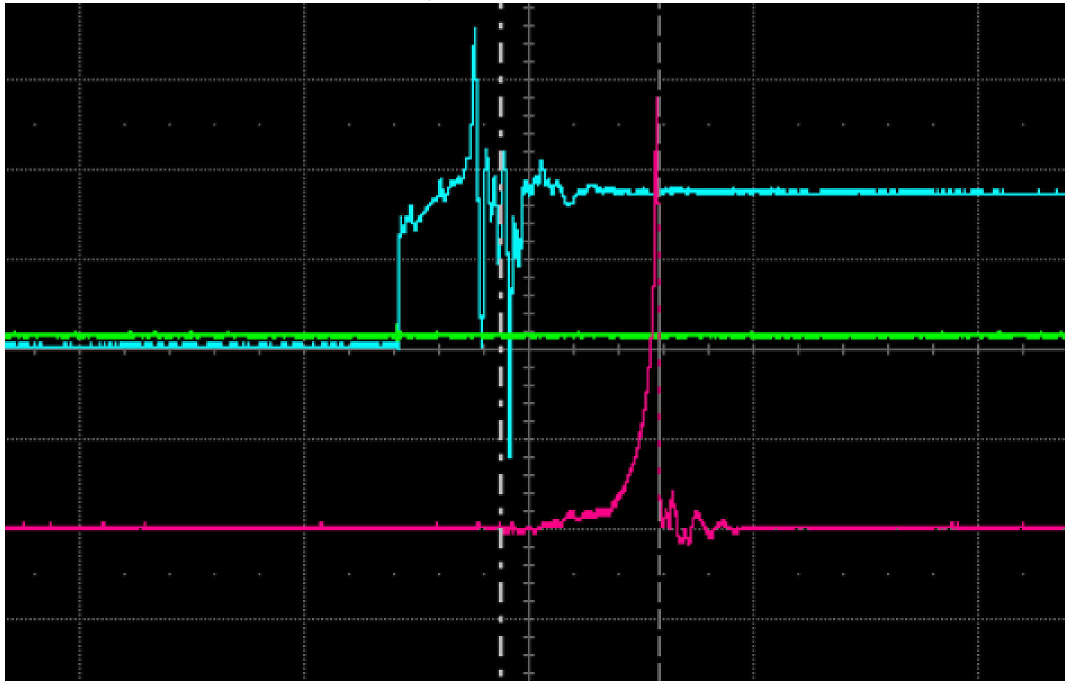
From August to November, we had 3 months of pbar beam time at CERN…

Results of 2021 pbar run

- Deceleration was achieved down to 4keV

6keV beam on MCP2

Signal in MCP2



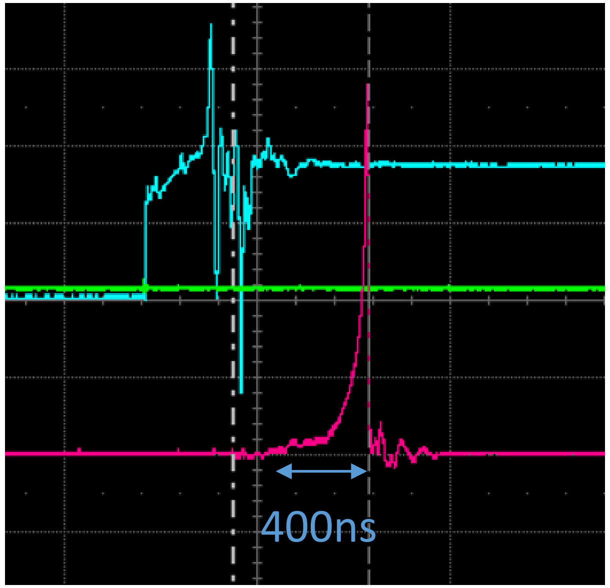
➔ **Check particles energy with TOF**

Results of 2021 pbar run

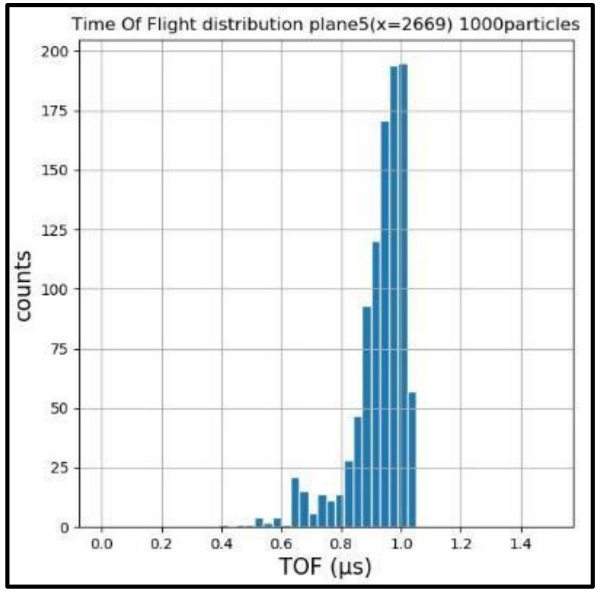
- Deceleration was achieved down to 4keV
- Matching with simulation expectations

6keV

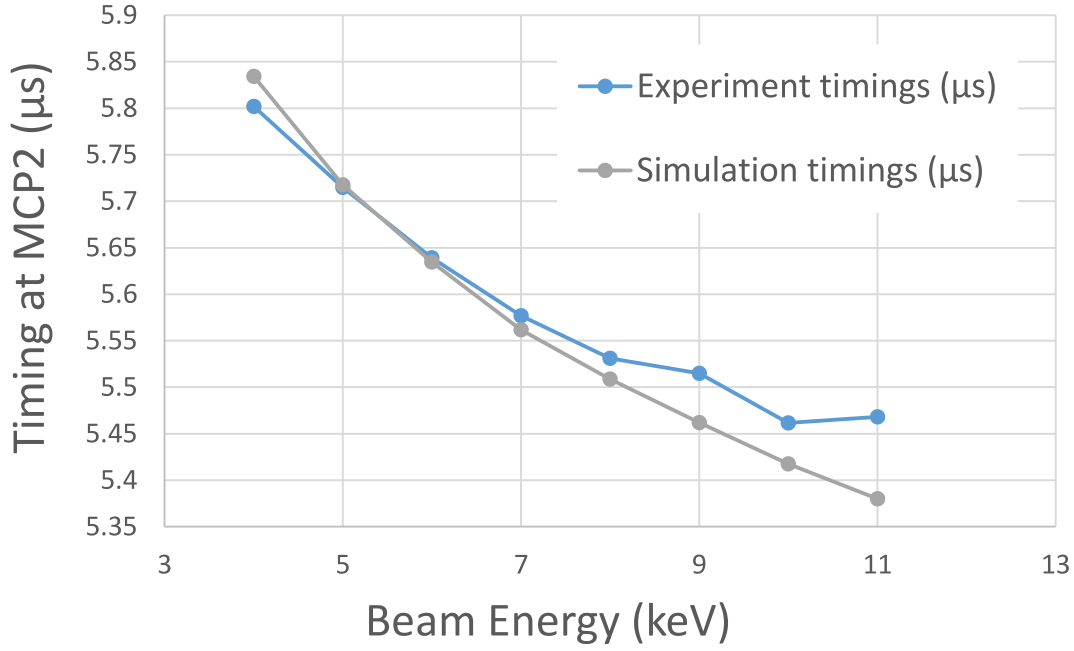
Signal in MCP2



Simulation

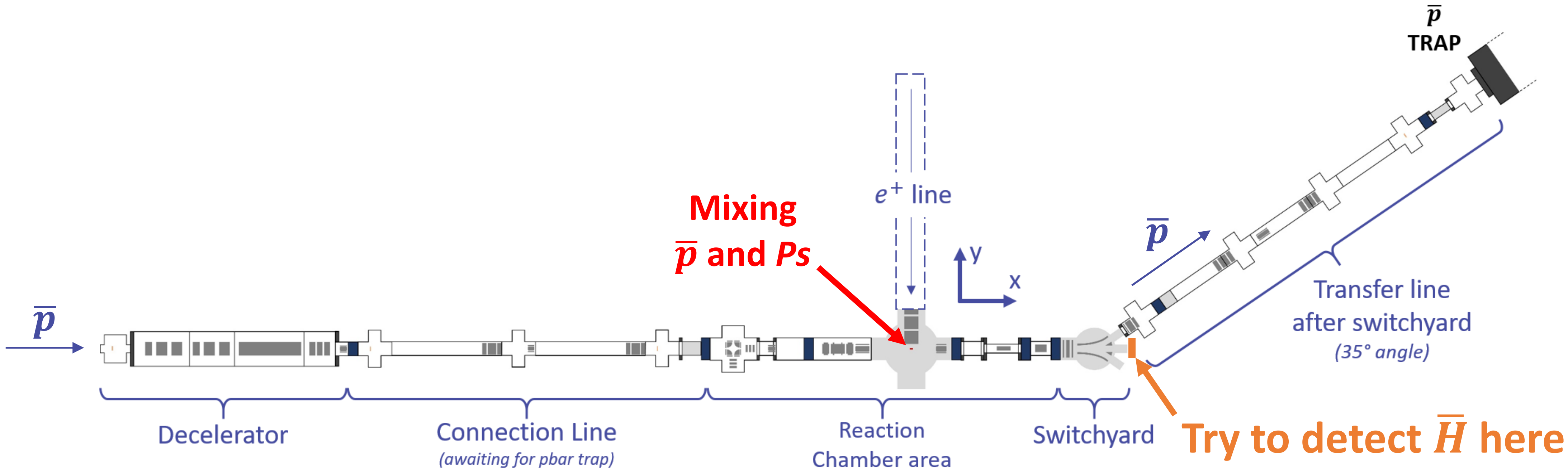


Energy scan



Results of 2021 pbar run

- Deceleration was achieved down to 4keV
- Matching with simulation expectations
- Transport up to reaction chamber & first mixings with Ps



Results of 2021 pbar run

- Deceleration was achieved down to 4keV
- Matching with simulation expectations
- Transport up to reaction chamber & mixing with Ps
- We had to face several technical problems preventing us from operating with optimal parameters *(ex: beam at 20keV instead of 6keV)*
- Background measurements *(from $\bar{p}$, Ps, AD hall environment)*

Next steps

- Some problems have been fixed during shutdown

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Cross section measurements

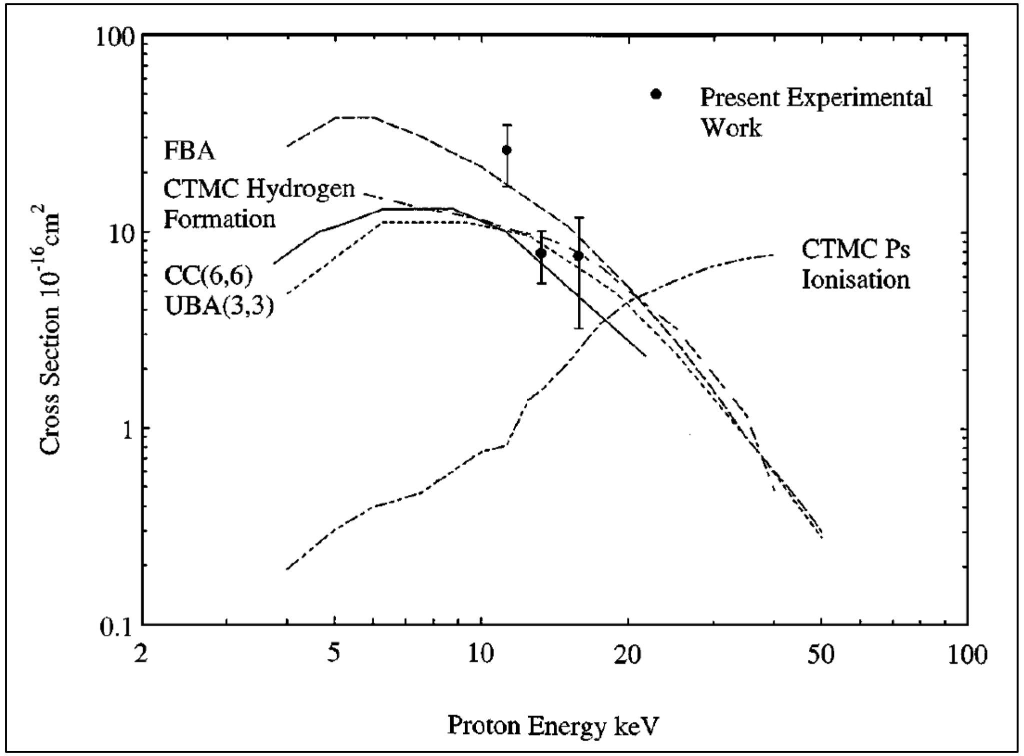

FIG. 2. Total cross sections for formation of hydrogen by proton impact upon Ps(1s) [2]

$$\text{Ps} + p \longrightarrow H + e^{+}$$

- *11.3keV*
- *13.3keV*
- *15.8kEV*

▶ CPT symmetry

[2] J.P.Merrison et al., «Hydrogen Formation by Proton Impact on Positronium,» *Phys. Rev. Lett.*, **78**, 14, 2728-2731, (1997)

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- 2022 run has begun one month ago
- Looking forward to try again $\bar{\mathrm{H}}$ **production** with optimal parameters
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- Installation of pbar trap ▶ Lower emittance, better focusing into target

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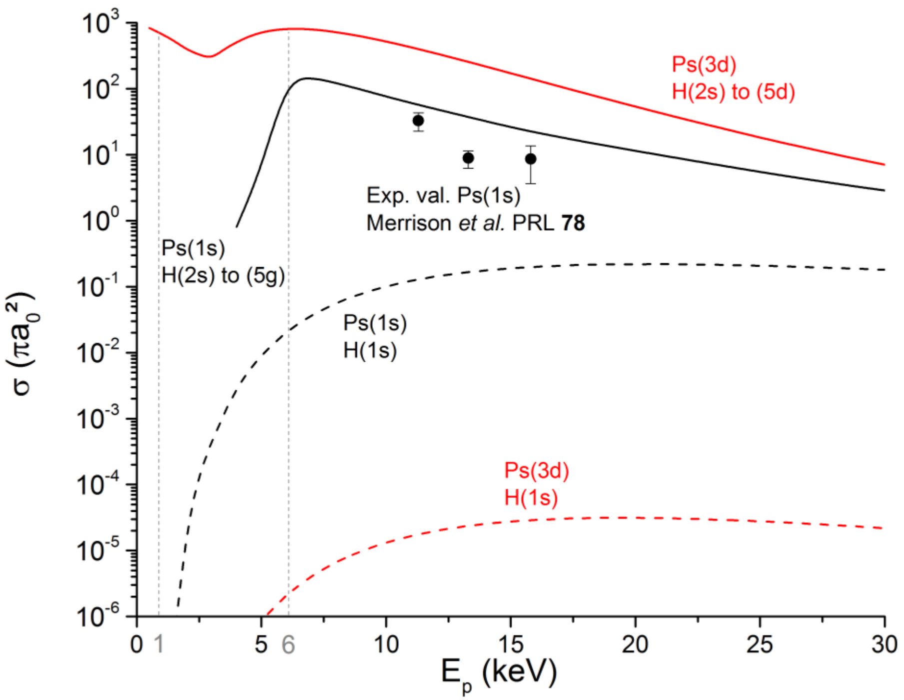
- Further steps: - second reaction cross-section measurement ▶ Never done

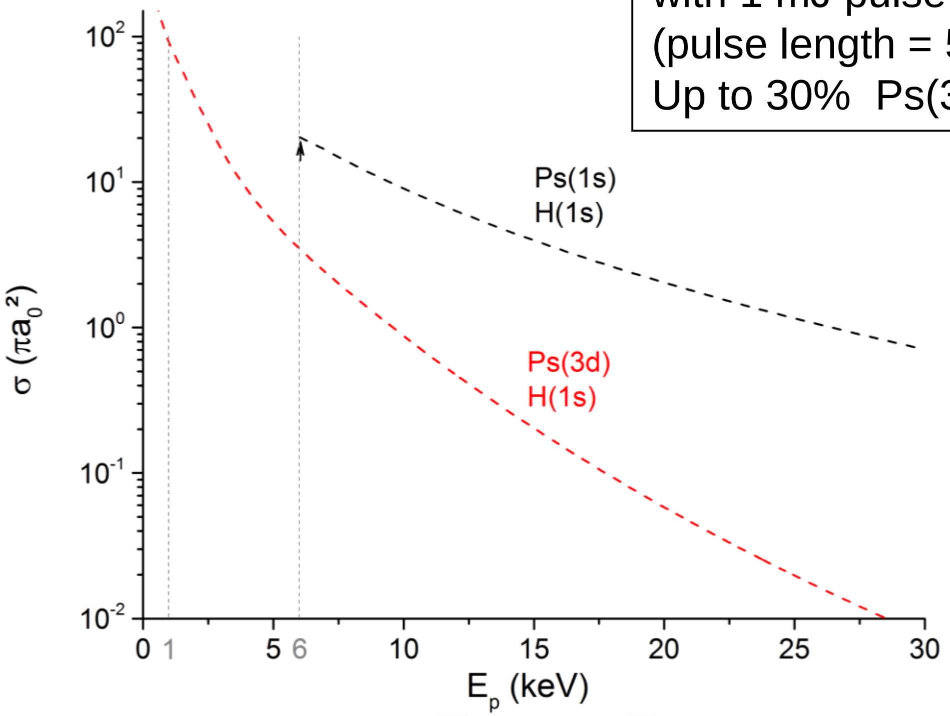
Cross sections theoretical calculations

1st Reaction



Production of excited $\overline{\mathrm{H}}$ from $\bar{\mathrm{p}}$

2nd Reaction



Production of $\overline{\mathrm{H}}^+$ from $\overline{\mathrm{H}}(1s)$

Laser 410 nm :
with 1 mJ pulse
(pulse length = 50 ns)
Up to 30% Ps(3d) available

$\overline{\mathrm{H}}$ de-excitation required

[3] P. Comini and P-A. Hervieux, «$\overline{H}^+$ ion production from collisions between antiprotons and excited positronium: cross sections calculations in the framework of the GBAR experiment» *New Journal of Physics*, **15**, 095022 (2013).

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  - install free-fall chamber and measure $\bar{g}$!

Thank you for listening !

References

1. H. Pihan-le Bars et al., "New Test of Lorentz Invariance Using the MICROSCOPE Space Mission" *Phys. Rev. Lett.* **123**, *231102,* (2019).

2. J. P. Merrison et al., «Hydrogen Formation by Proton Impact on Positronium,» Phys. Rev. Lett., **78**, 14, 2728-2731, (1997).

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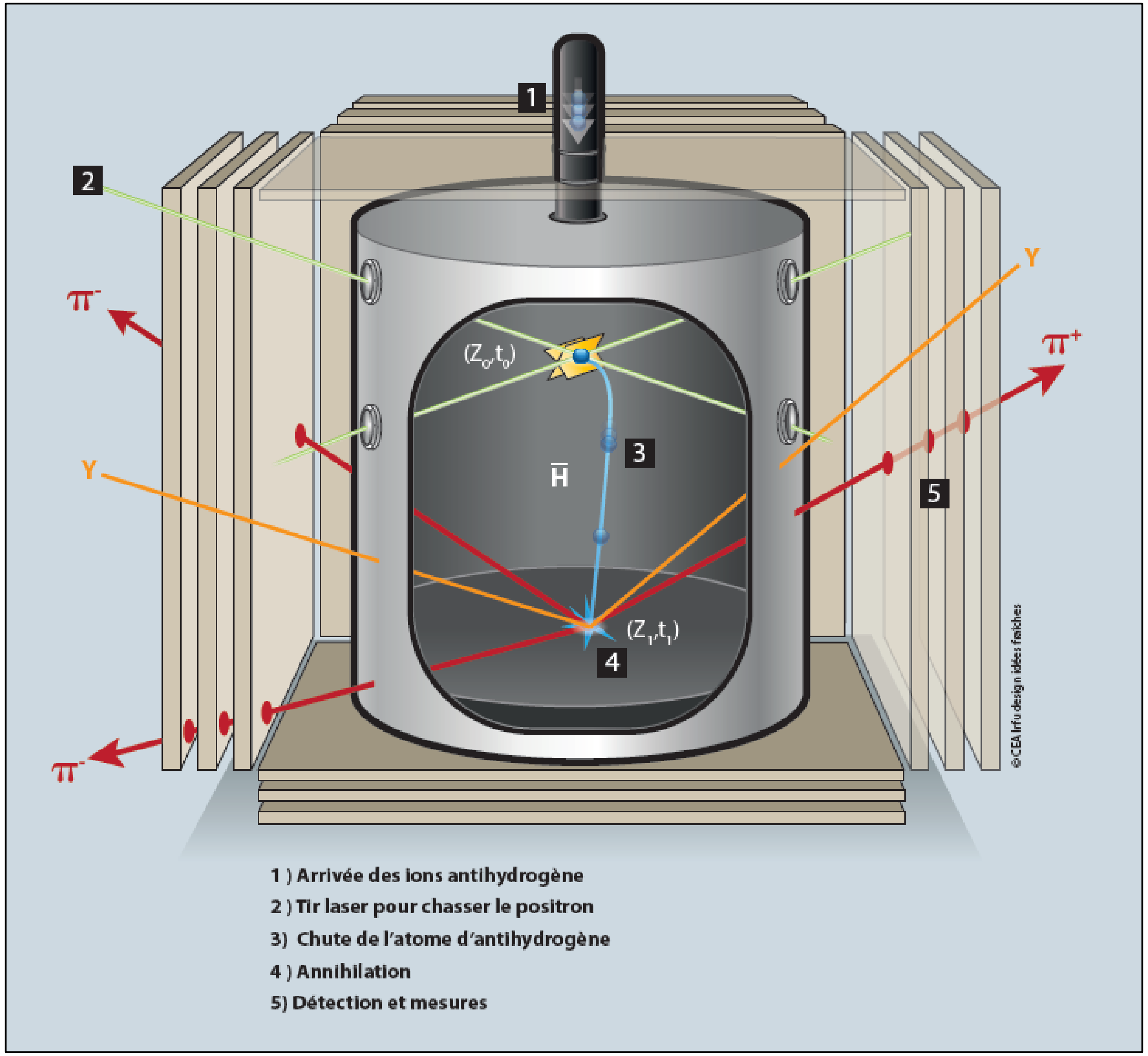
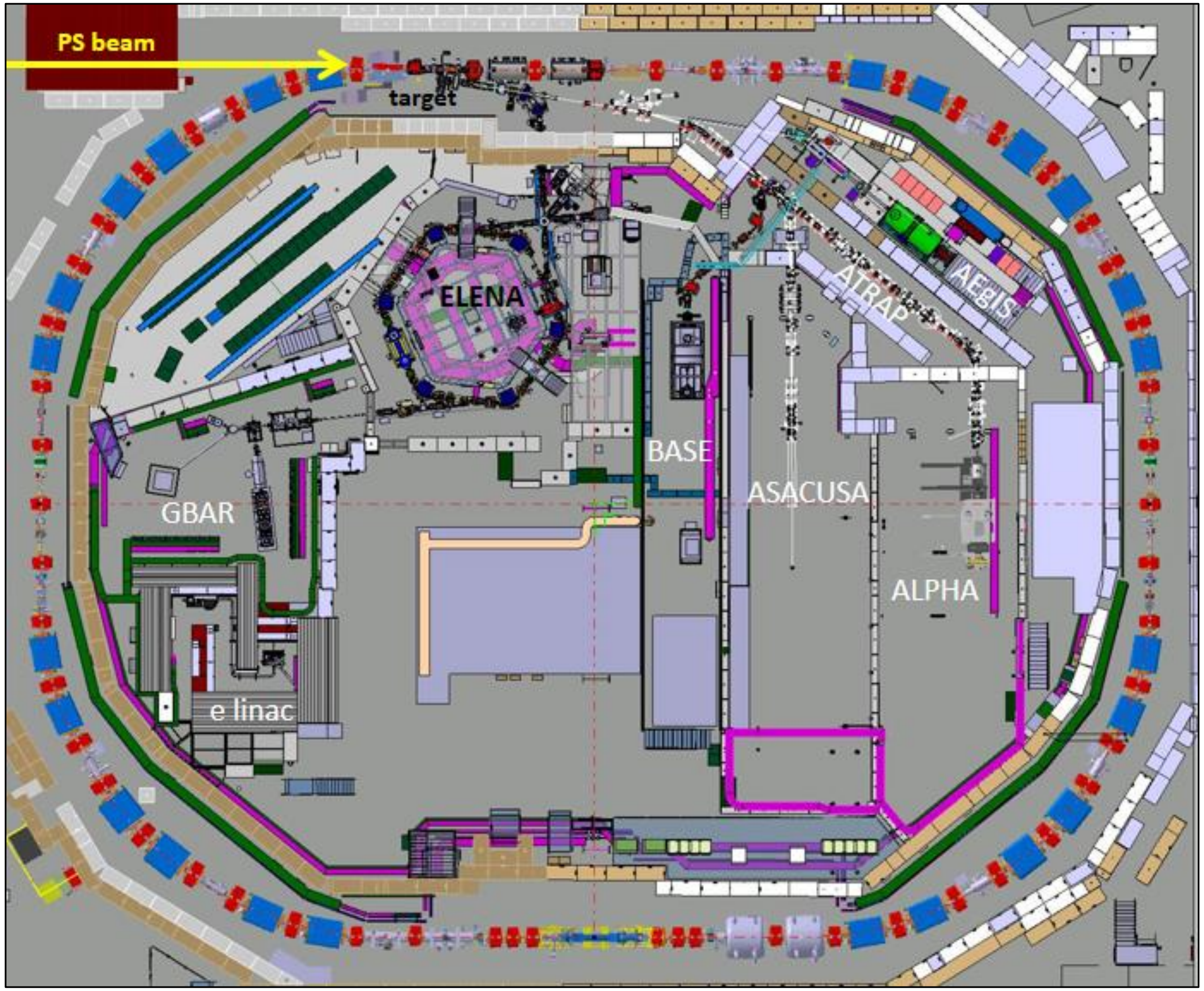
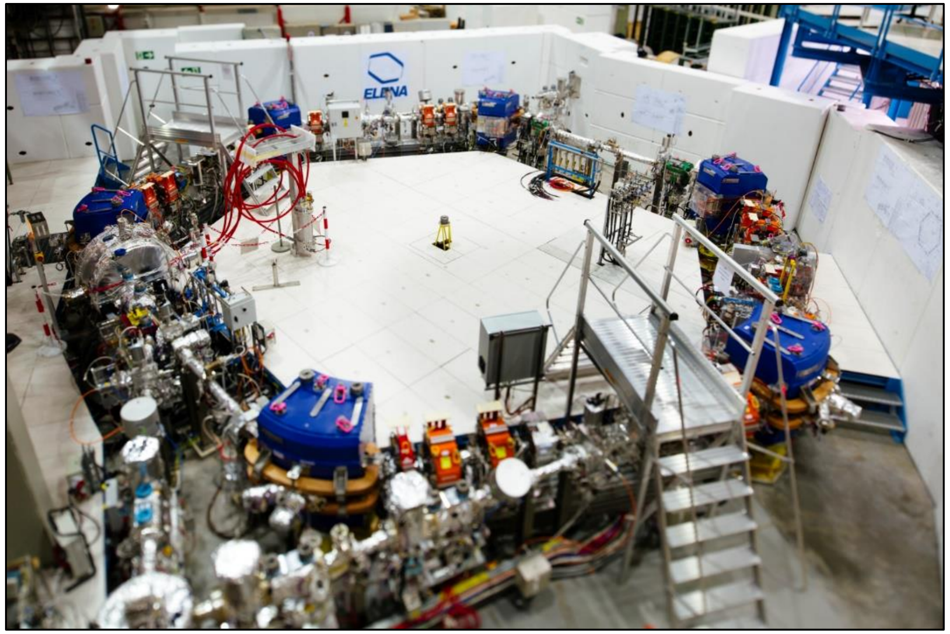
Backup slides

Free-fall Chamber scheme



AD hall

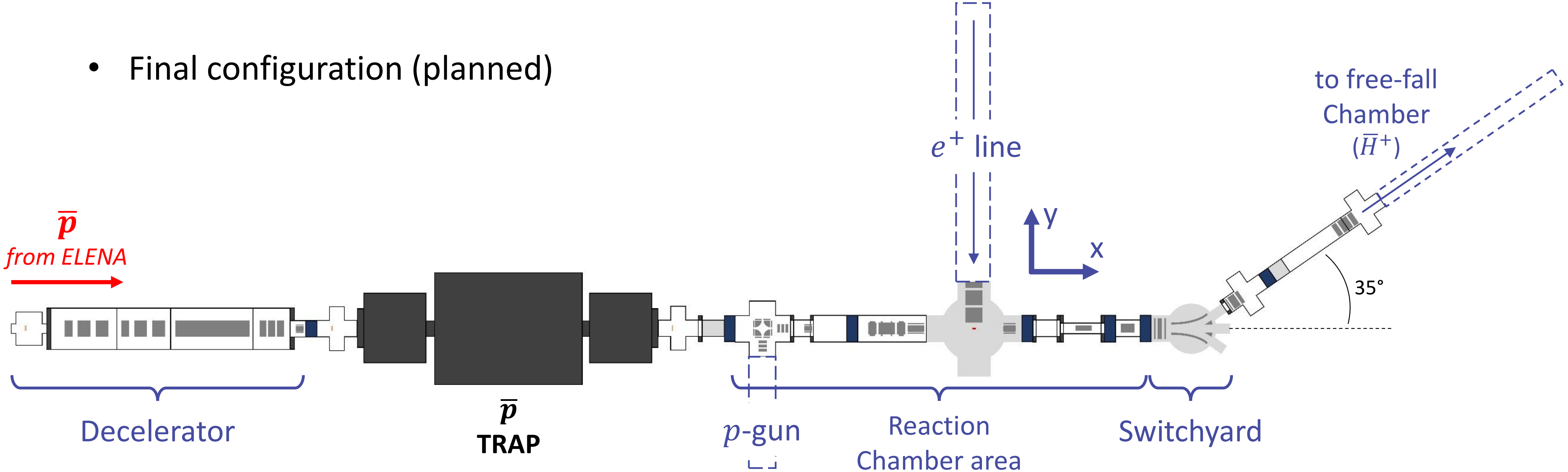




ELENA Ring

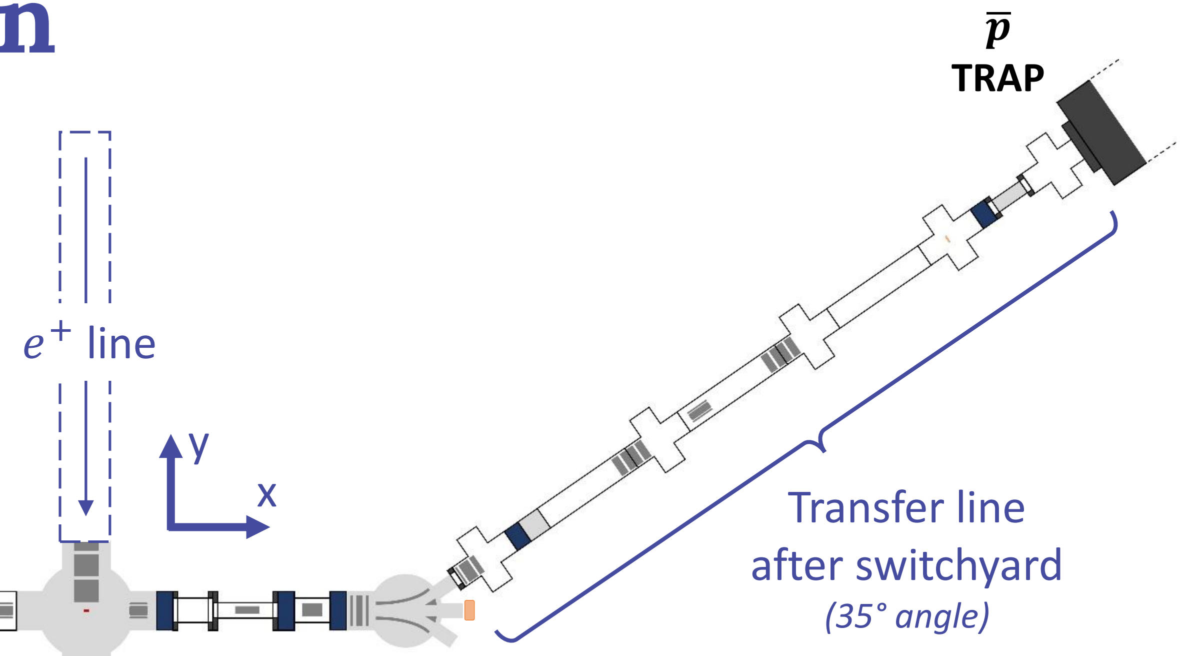
Pbar line scheme – design

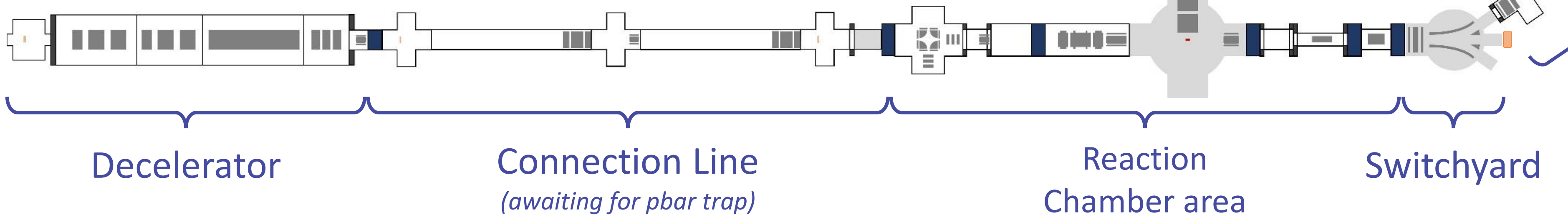
- Final configuration (planned)

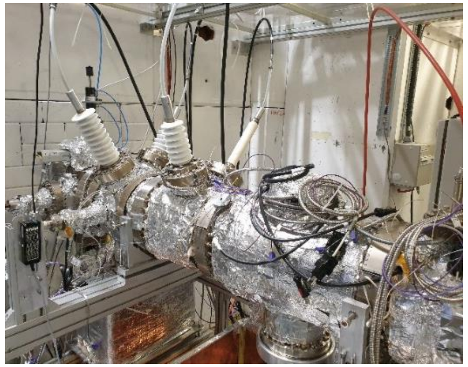


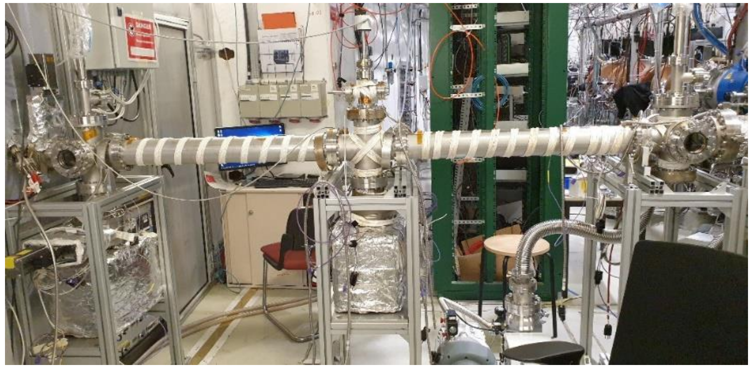
Pbar line scheme for 2021 run

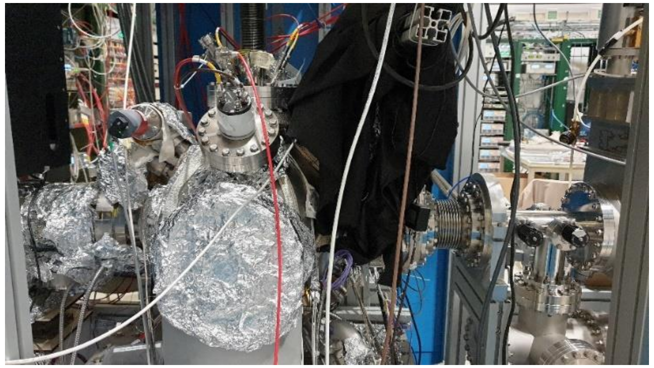
- $\bar{p}$ trap at the end of the line
- Temporary line between decelerator and reaction chamber
- <u>Goals:</u> Detect $\bar{H}$ in switchyard MCP & test $\bar{p}$ trap

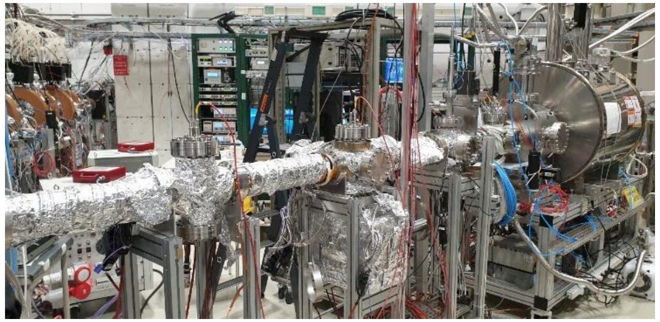






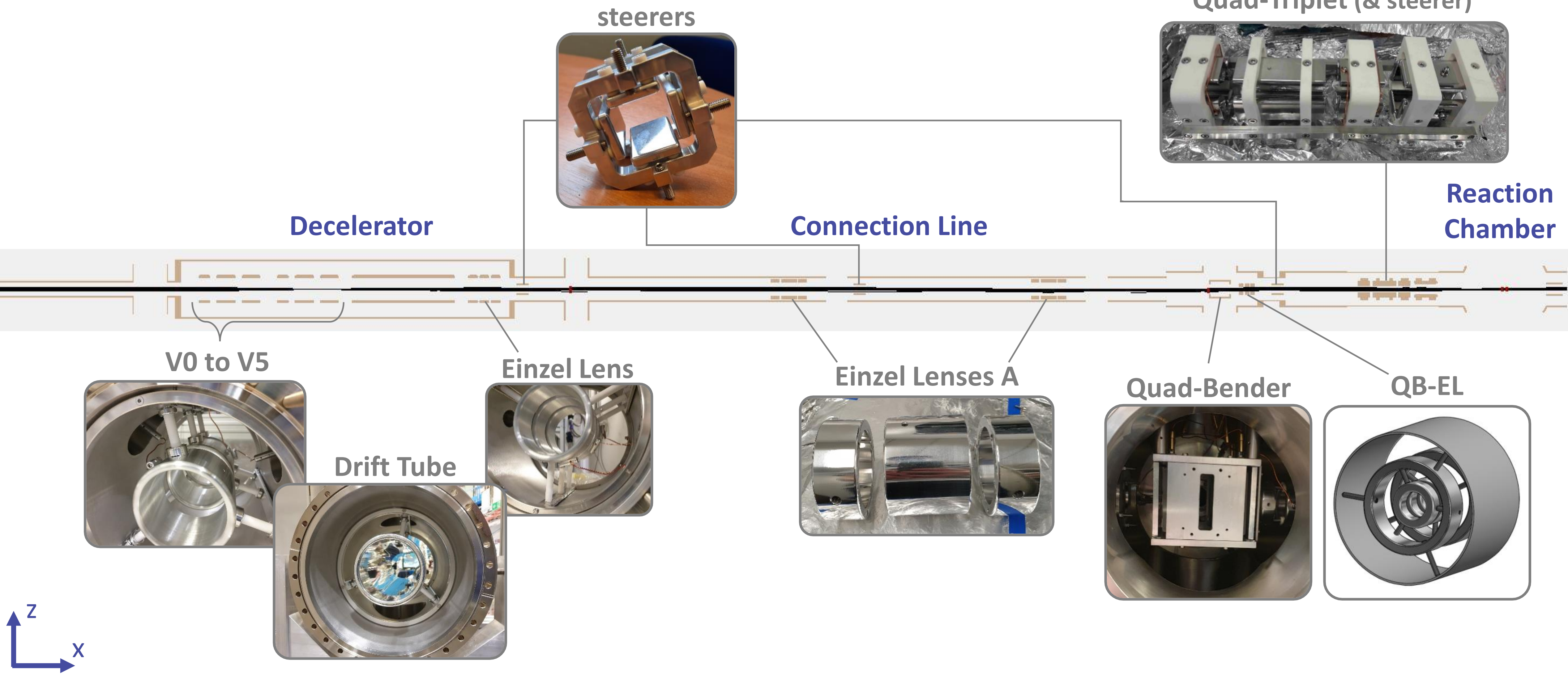




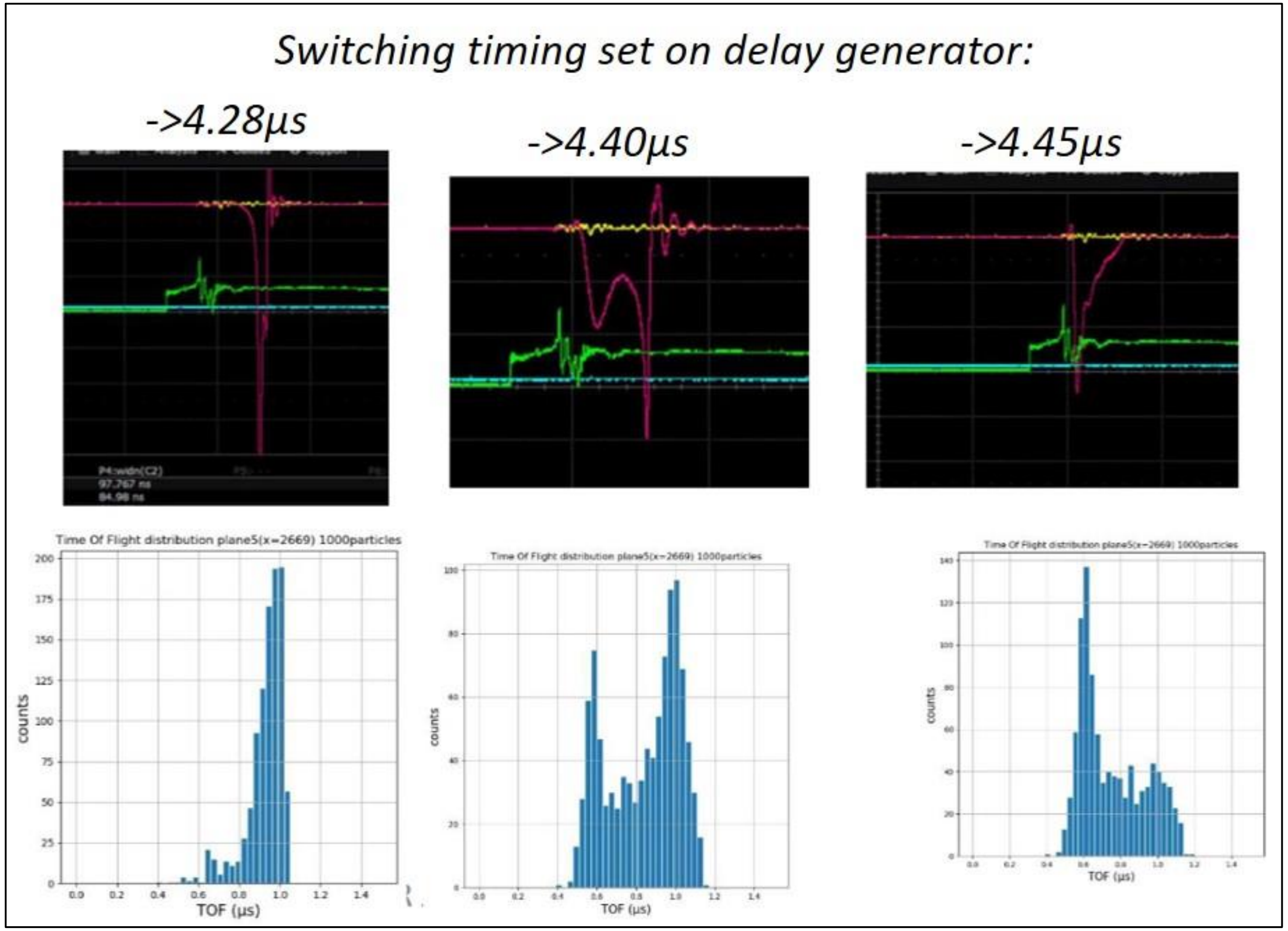


SIMION Simulation – ‘Optical’ elements

Transport and focus on target in reaction chamber



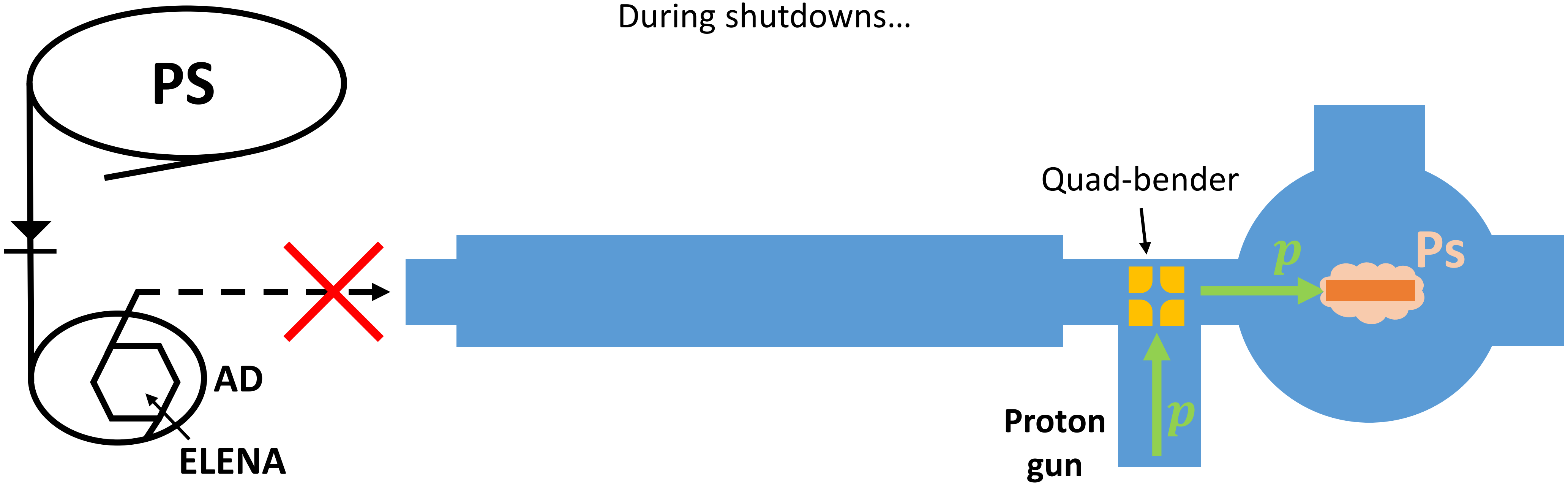
Experiment vs Simulation – switch timing



- Matching experimental signal on MCP2 with expected timing distribution for different switch trigger timings

Operating with protons

During shutdowns…

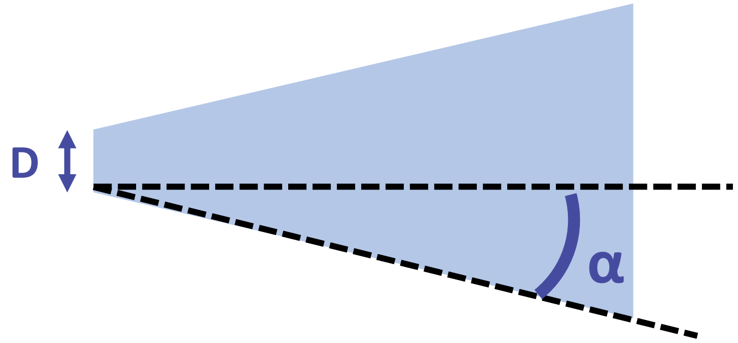


- Matter equivalent reactions

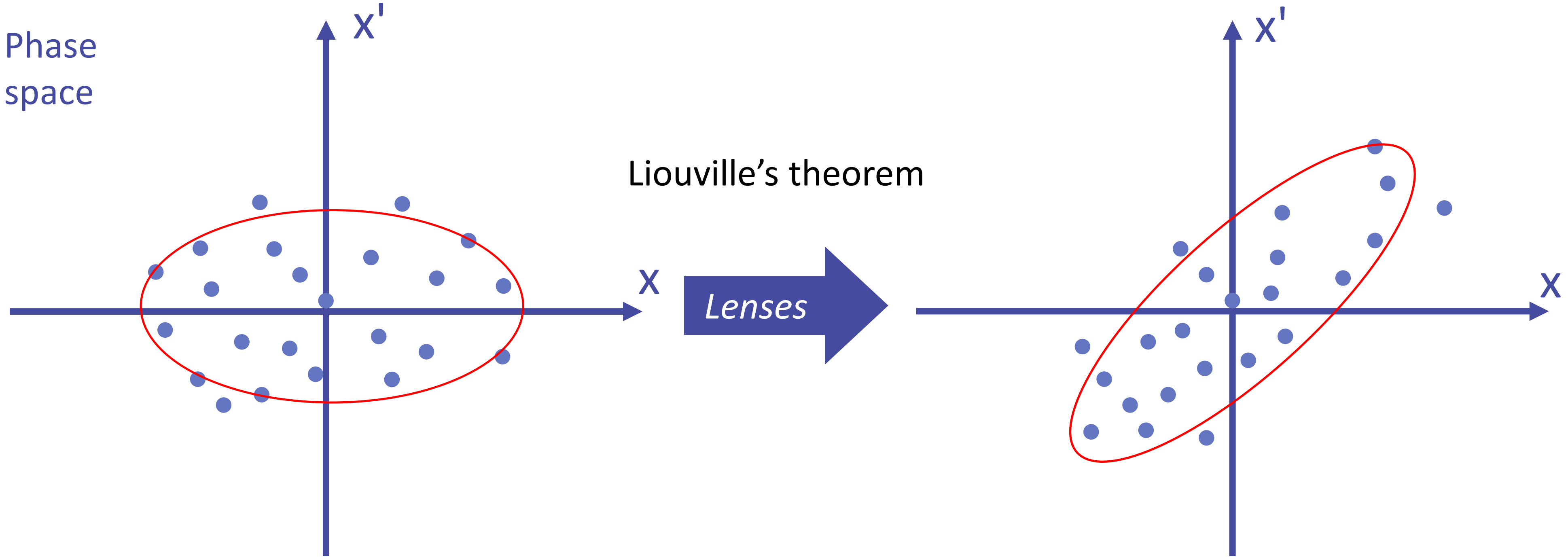
$$(1') \quad Ps + p \longrightarrow H + e^+$$

$$(2') \quad H + Ps \longrightarrow H^- + e^+$$

Emittance



$$\text{Émittance} = \frac{1}{2} D \times \alpha \qquad [mm.mrad]$$



ELENA beam

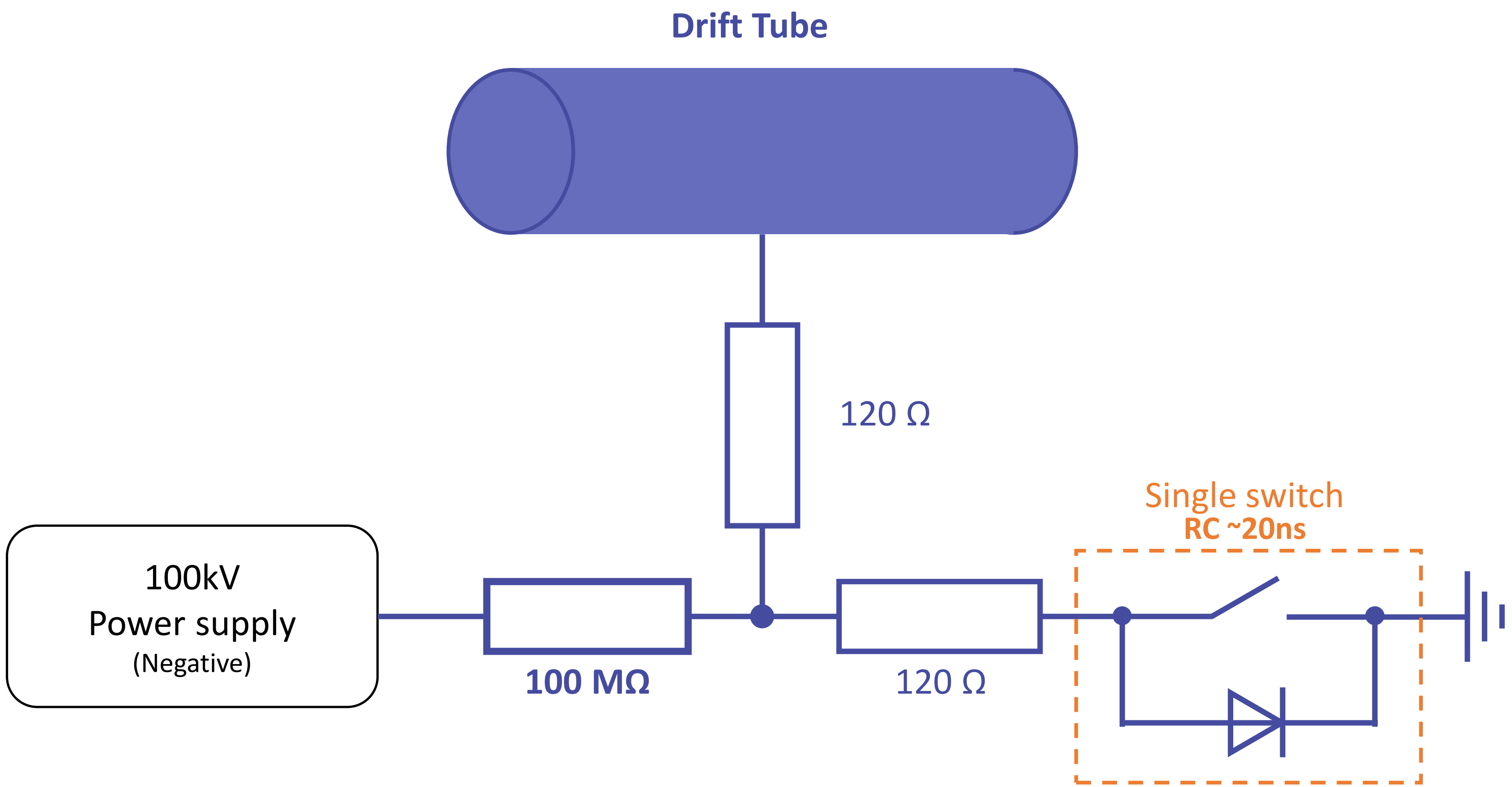
- Nominal ELENA beam parameters:

Parameter at ejection[a]		Baseline four bunches
Number of bunches	4	
Bunch population	0.45×10^7 antiprotons	
Relative Momentum spread	0.5×10^{-3}	R.m.s. value
Bunch length	75 ns	R.m.s. value
Horizontal emittance	1.2 µm	R.m.s., physical
Vertical emittance	0.75 µm	R.m.s., physical

- Parameters during 2021 beamtime:
  - dp/p ~ 0.5e-3, *ie* **50eV**
  - Bunch length ~ **65ns σ**
  - Horizontal emittance ~ **1.6 - 2.5 µm**
  - Vertical emittance ~ **1.6 - 2.5 µm**
  - Extraction time jitter ~ **5ns σ**

- For the last 2 days of beamtime, ELENA team implemented bunch rotation:
  - Bunch length ~ **40ns σ**
  - Energy spread is higher with bunch rotation. Estimated to twice the nominal value → still ok for Gbar

Drift tube HV switch setup



switch open → HV on DT → V_drop = I_leak x R
switch closed → DT at GND